Fiber Optics (FO)

Introduction:- Communication is defined as a process of "Sending and receiving information/data from one place to another in a faithfull manner."

In scientific language, the communication has been classified in two broad categories (i) Line/wire or Guided Communication (ii) Wireless or unguided communication.

To understand the difference between these two types of communication, we must have the knowledge of source (sender), medium or channel and receiver.

The source/sender is a body (may be a device also), which generates information, while receiver is a body or device, which receives and interprets information. The source and receiver are usually separated from each other (the separation can be a few meters upto several Astronomical units also). The medium through which information or signal travels from source to receiver is called medium or channel.

"If the boundaries of medium or channel between source and receiver are well defined, then such a communication is called Line/wire or unguided communication, while if the boundaries of channel or medium are not well defined, then communication is called wireless or unguided communication".

Examples of line/guided communication are broadband internet, landline telephone, cable TV etc. While examples of unguided communication are mobile, wireless, television, speech of a teacher in a classroom, satellite or dish antenna, ~~etc~~ wifi etc.

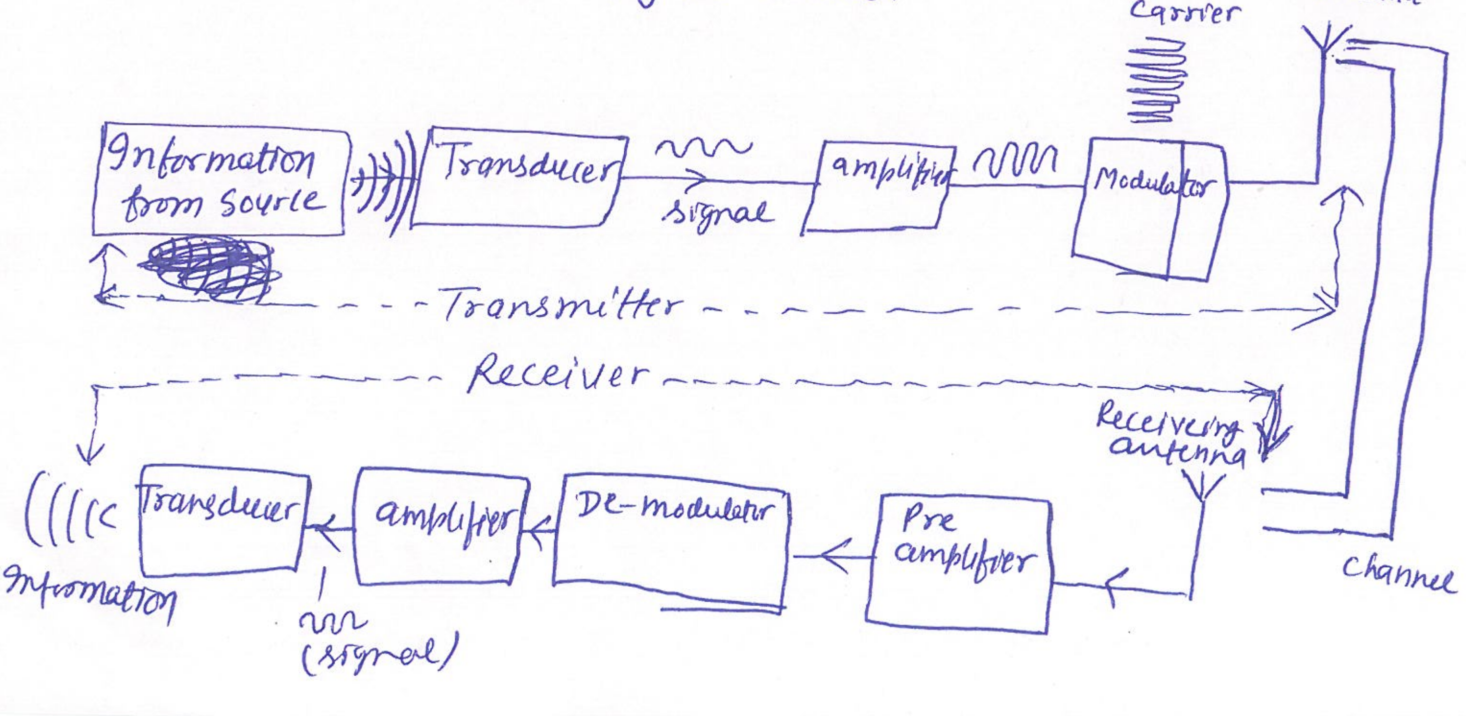
Both of these kinds of communication have ~~th~~ their separate domains of applications, advantages and disadvantages.

Wireless communication has been further classified as space wave, sky wave, ground wave and satellite communication.

Similarly line communication is also classified into two sub categories viz; electric communication and optical communication.

Sometimes the information/data to be sent/transmitted from one place to another may be very important and if it is received by an unwanted receipient, it may be misused. For such cases information security becomes a vital issue. This was the prime reason to shift from analog to digital communication. In case of analog communication, the signal is sent from one place to another place in the form of a continuously varying voltage or optical signal, while for digital communication, signal is encoded into bits in the form of 0s and 1s before being transmitted and only a proper recipient / receiver having decoding device will be able to retrive the information. Therefore, digital communication is much more secure than analog communication.

In this chapter, our main focus will be on optical communication through optical fibers, which is a sub-category of line/guided communication. The typical block diagram of a line communication system is shown in the figure below:



It should be noted that information and signal are different from each other. Let us take an example of speech communication by a professor to a class, which is at thousands of miles from him, using broadband optical ~~fibers~~ fibers (internet). In such an example the words he is speaking come out in air as sound waves. These sound waves are said to define information. Obviously he is speaking different words to deliver his lecture, therfore it is clear that information is never monochromatic (i.e. it is always polychromatic or contains large number of frequencies).

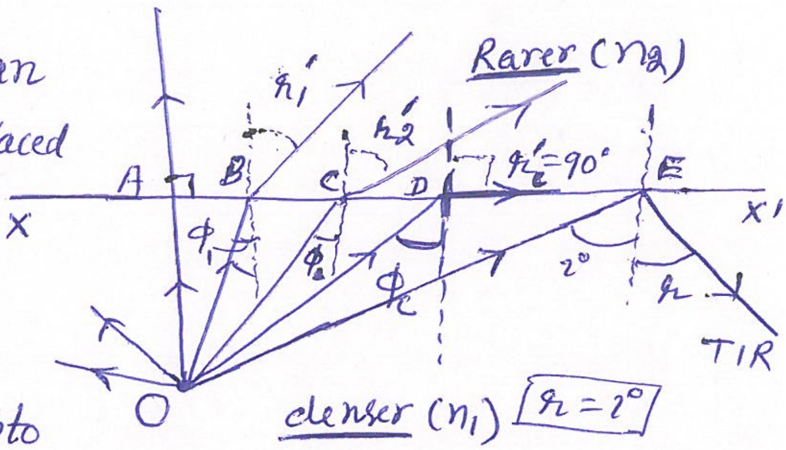
Now he has a collar mic just near his mouth on his shirt. This mic takes sound waves as input and converts these into electrical waves. These output electrical waves are called "signal waves". Since the frequency of information is changing from time to time, therfore frequency of signal is also changing from time to time (because there is one-to-one correspondence between information and signal waves). Thus just like information, signal waves are also of varying frequencies. For a speech ~~signal~~ communication the information varies in the frequency range of 20 Hz — 20 kHz (and can be heard by human ear), therefore the frequency of signal waves generated by mic also ranges from 20 Hz — 20 kHz (however these cannot be heard by human ear). Now the output of mic (electrical signals in the range 20 Hz – 20 kHz) is given as input to an appropriate optical device (one may assume a light emitting diode as simplest example in his mind here), which converts ~~these optical~~ electrical signals into an optical signals again in the frequency range 20 Hz – 20 kHz (These waves are now electromagnetic waves, which of course cannot be heard, but still these are called audio frequency waves due to the reason that these carry information of speech). These signal waves are very weak (due to low frequency waves) and cannot be transmitted as such to large distances. Thus these signals are amplified and then mixed with a suitable, high frequency, monochromatic electromagnetic wave, which is called "carrier wave". It is therefore carrier wave, which is of ~~sign~~ single frequency and signal wave is never of ~~sign~~ single frequency.

Kindly remember that signal wave is weak, polychromatic, carries information in it (∵ it is generated by one-to-one correspondance with information), but it cannot reach upto longer distances. However carrier wave is strong (due to very high frequency), monochromatic and carries no information.

Therfore, when signal waves and carrier wave are mixed using appropriate device (called modulator), the resulting wave (called modulated wave) carries information and is strong enough to reach to long distances. (Please remember that nature of signal & carrier waves ~~This modulated wave is then transmitted into~~ must be same i.e. if signal waves are electrical in nature, then carrier waves must also be electrical waves. On the other hand if signal waves are optical/electromagnetic waves, then carrier waves must also be optical/electromagnetic waves).

This modulated wave is then transmitted in the optical fiber (broad band cable). At the other end of optical fiber, receiving antenna receives this modulated optical signal, this signal is firstly amplified and then demodulated (that is carrier and signal waves are separated from each other and then carrier waves are just rejected and signal waves are sent to next device for further processing). This signal wave is an electromagnetic wave, which is converted into an appropriate electric wave signal using a suitable device like a photo diode. The electric wave signal thus obtained is given as input to a loud speaker, which converts ~~int~~ it into sound. In this way we can send send speech from one place to another using optical cable. The process of sending information other than speech is exactly the same, however, the devices used to convert information into signal waves (optical and electric waves) have to be chosen accordingly. Such a device, which converts a physical quantity or information into an electric or optical signal and vice versa is called transducer.

Total Internal Reflection:- "When a ray of light is travelling in denser medium and it strikes at an interface with a rarer medium in such a way that the angle of incidence made by ray of light at the interface is greater than critical angle angle, then the ray is reflected back into denser medium. This phenomenon is called total internal reflection (TIR)."



__Explannation__ Figure shows an object (source of light) 'O' placed in a denser medium of refractive index (n_1). This denser medium extends upto certain region XX' of space, beyond that, a new rarer medium of refractive index (n_2) (i.e. $n_1 > n_2$) starts. Thus the surface XX' is the interface between two media. Light rays from 'O' originate in all possible directions as shown in the figure. Consider one such ray, which is incident normally at point A on the interface. For this ray, the angle of incidence is 0°, therefore, this ray does not obey Snell's law and hence it enters from denser to rarer medium without any deviation or change in path.

Another ray from O is incident at point B of interface, such that angle of incidence ϕ_1 is not zero. This ray

$\mu \ll 0$

will obey Snell's law and hence bends away from normal while crossing the interface. If r_1' is angle of refraction at B, then we can apply Snell's law at B as follows:

$$\begin{pmatrix}\text{refractive index of} \\ \text{first medium}\end{pmatrix} \times \begin{pmatrix}\text{Sine of angle of} \\ \text{incidence in first} \\ \text{medium}\end{pmatrix} = \begin{pmatrix}\text{refractive} \\ \text{index of} \\ \text{second} \\ \text{medium}\end{pmatrix} \times \begin{pmatrix}\text{Sine of} \\ \text{angle of} \\ \text{refraction} \\ \text{in second} \\ \text{medium}\end{pmatrix}$$

or $n_1 \times \sin\phi_1 = n_2 \times \sin r_1'$

$$\Rightarrow \sin r_1' = \frac{n_1}{n_2} \sin\phi_1 \quad \text{---(1)}$$

Another ray from 'O' strikes at point 'C' on the interface, where angle of incidence is ϕ_2 and angle of refraction is r_2'. Then using Snell's law at point 'C', we can write

$$\sin r_2' = \frac{n_1}{n_2} \sin\phi_2 \quad \text{---(2)}$$

Since point C is farther from A as compared to point B (i.e. $AC > AB$), therefore, it is clear that $\phi_2 > \phi_1$.

Next we must remember that angle of incidence or angle of reflection or angle of refraction can never be more than 90°. Another point to recall is that Sine function is an increasing function in first quadrant of trigonometric quadrant table (while cosine function is a decreasing function in first quadrant). Thus

$\phi_2 > \phi_1$ would simply mean that $r_2 > r_1$. This allows us to conclude that as we move farther from point of normal incidence (A), in any direction on the interface, the angle of refraction goes on increasing i.e. the refracted ray would bend more and more toward the interface (or more and more away from normal). Continuing this explannation to even farther points, we can notice that a point 'D' must be achieved on the interface, where the angle of refraction (r') has maximum possible value (i.e. 90°). At this point, the refracted ray grazes along the interface and angle of incidence in the denser medium is called <u>critical angle</u> (ϕ_c). If we apply Snell's law at point D, we get ~~Sin φ~~ $\sin r'_c = \frac{n_1}{n_2} \sin \phi_c$

$$\Rightarrow 1 = \frac{n_1}{n_2} \sin \phi_c \quad (\because r'_c = 90°)$$

$$\Rightarrow \boxed{\sin \phi_c = \frac{n_2}{n_1}}$$

Now if a ray of light from 'O' is incidence on some point E beyond point of glacing refraction (D), then it will bend further away from normal in rarer medium and will come back into the denser medium.

Such a ray is said to have suffered total internal reflection (TIR).
Thus conditions for TIR to take place are as follows:

(i) Ray of light must be incident from denser to rarer medium
(ii) The angle of incidence at the interface must be greater than critical angle.

Optical Fibers (construction and principle of working)

"An optical fiber is defined as thin and flexible medium, which can transfer optical signals from one place

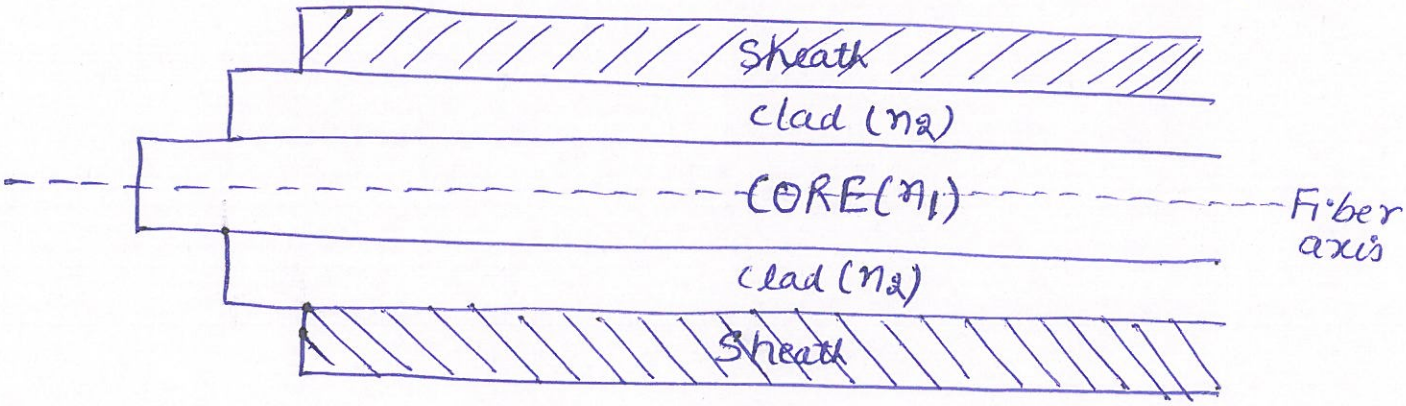


Fig. 1

to another." The basic diagram of an optical fiber is shown in figure 1 above. It contains three co-axial cylindrical layers known as core, clad and sheath (or buffer jacket).

Core : This is the innermost layer of optical fiber. It is an optically transparent layer made from glass or plastic having refractive index n_1, which is slightly more than the refractive index of next layer surrounding it. The diameter of core can be in the range ~(10–60) μm.

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They rays of light (optically modulated waves) are confined within this layer only (principally & not practically), during transmission from input face to output end of optical fiber.

Clad: The layer surrounding ~~clad is~~ core is called clad. This layer is also optically transparent and made from glass or plastic just like core. However its thickness ~~is~~ (~125 μm) is very large as compared to core diameter (~(10-60) μm), so as to give extra strength to the fiber. The refractive index of clad (n_2) is ~~greater than~~ slightly smaller than refractive index of core (i.e. $n_1 > n_2$), so that condition of TIR may be satisfied, when optical signals travel within core. The refractive index difference between core and clad is kept very small so as to minimize transit time dispersion (also called as inter-modal dispersion delay), which is a major cause of signal distortion in optical fiber.

Sheath: This is outermost layer of optical fiber surrounding the clad. It is opaque and made from rubber or PVC. This layer can have a thickness of the order of a millimeter. It has no role to play in the optical transmission of signals.

This layer gives extra strength and flexibility to optical fiber and protects the fiber from ambient changes like temp., pressure, moisture etc. Since this layer does not play any role in the optical transmission, therefore, during theoretical discussions of fiber optics, we can ignore this layer in the figures.

Principle of working:- The working of optical fiber is understood in simplest way by analyzing figure (2). Here three different

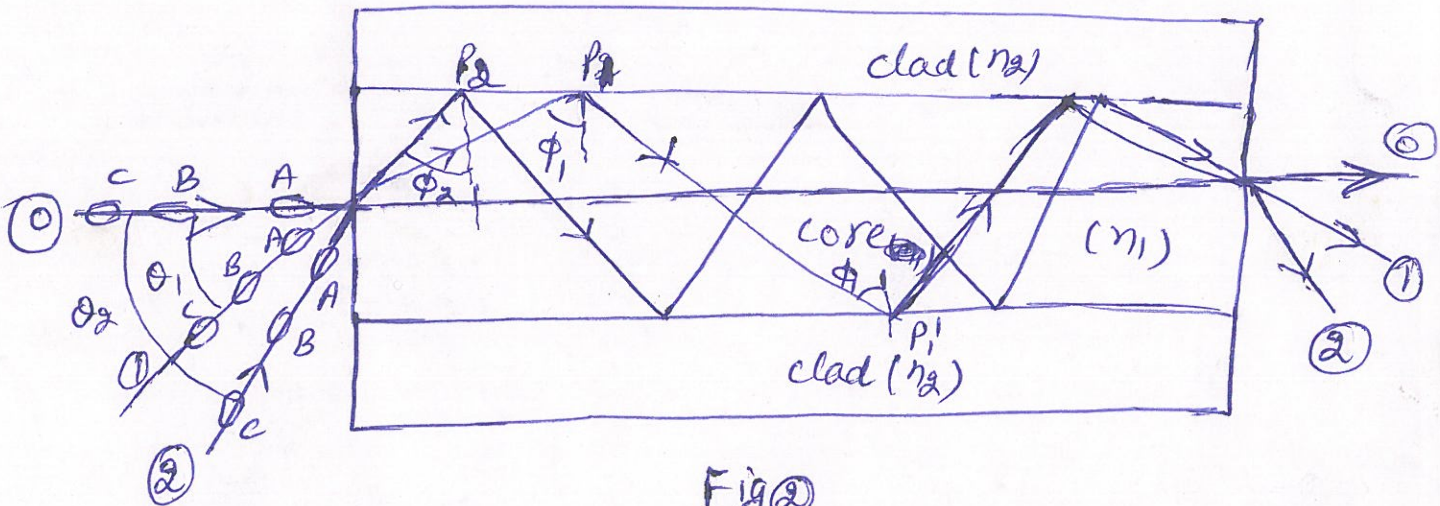


Fig (2)

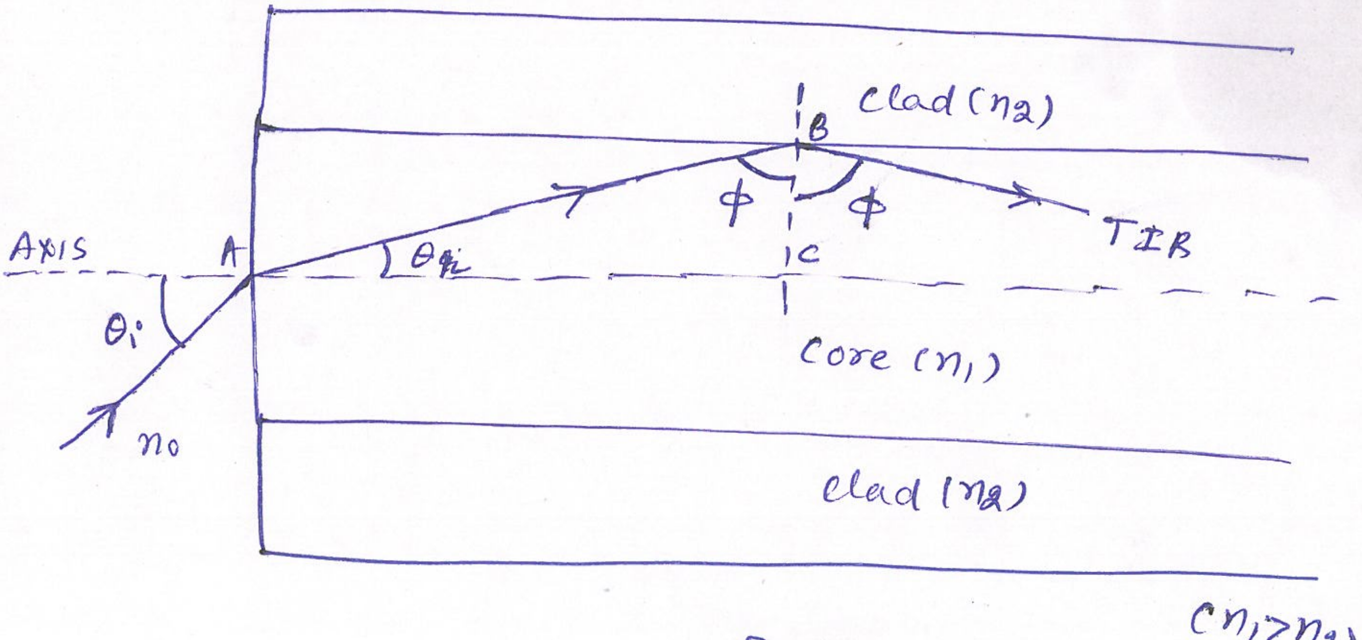
rays of light identified as (0), (1) and (2) are incident on the optical fiber, such that angle of incidence is 0° for ray (0), and it is θ_1 for ray (1) & θ_2 for ray (2) at the time of entering in optical fiber (where $0° < \theta_1 < \theta_2$). We assume that there is no bend in optical fiber. Therefore ray (0) will travel along axis of optical fiber. On the other hand ray (1) will bend slightly toward axis of fiber, while entering in the core. On entering core, the ray travels along straight path OP_1, where point P_1 is on the core clad interface. This ray is making angle ϕ_1 with normal drawn at P_1. If ϕ_1 is greater than value of critical angle ϕ_c (where $\sin\phi_c = \frac{n_2}{n_1}$) between core and clad, then it will suffer TIR at P_1 and it will go toward point P_1'. Since there is no bend in fiber, therefore angle at P_1' will also be ϕ_1, which is again greater than ϕ_c. This process will continue till the ray reaches other end of fiber, and eventually ray of light comes out of other end of fiber by suffering refraction. Similar behaviour will be shown by ray (2), with only difference that due to greater angle of incidence (θ_2) at the time of entering in the fiber, its path within the fiber will be longer than path of ray (1) and it will suffer more number of TIRs at core-clad interface while travelling from one end to other end of fiber. Thus at the output we will get ray (0) followed by ray (1) & then ray (2) & so on. Thus we can sum up that light waves are transmitted through optical fibers via "multiple total internal reflections."

Acceptance angle and numerical aperture of optical fiber:-

In the previous article we observed that since $\theta_2 > \theta_1$, thus $\phi_2 < \phi_1$. It means for a ~~given~~ given value of critical angle ϕ_c between core and clad, the difference

$\phi_1 - \phi_c$ is more than $\phi_2 - \phi_c$ (e.g. if $\phi_c = 70°$, $\phi_1 = 80°$, $\phi_2 = 75°$, $\phi_1 - \phi_c = 10°$ & $\phi_2 - \phi_c = 5°$). It means ϕ_2 is more close to ϕ_c as compared to ϕ_1. This simply indicates if the angle of incidence with axis ~~of fiber~~ at the time of entering in the fiber, then chances of TIR at core-clad interface within fiber are small. Hence in general the angle of incidence with axis of fiber at input cannot be increased beyond a certain limit.

Hence acceptance angle (θ_0) is defined as "maximum value of angle of incidence at the input of optical fiber, such that a ray of light just suffers TIR at core-clad interface".



Fig(1)

Consider an arbitrary ray of light make angle θ_i with axis of optical fiber, at input as shown in Fig 1. On entering the optical fiber, it bends toward axis due to refraction and angle of refraction is θ_R. This refracted ray strikes core-clad interface at point B. Let it makes angle ϕ with normal drawn to core clad interface at ~~point~~ B. It is clear from ΔABC that $\theta_R + \phi = 90°$ —— ① ($\because \angle ACB = 90°$)

Let n_0 = refractive index of surrounding medium
n_1 = " " " core
n_2 = " " " clad

(Note that $n_0 < n_2 < n_1$)

Apply Snell's law at point A, we get

$$n_0 \times \sin\theta_i° = n_1 \times \sin\theta_R$$
$$= n_1 \times \sin(90-\phi) \quad (\text{using ①})$$
$$= n_1 \cos\phi$$

$$\Rightarrow \sin\theta_i° = \frac{n_1}{n_0}\cos\phi \quad \text{—— (2)}$$

Since ray of light shown in fig 1. arbitrary, therefore by increasing its value, we may reach maximum value of $\theta_i°$ denoted by symbol θ_0, called acceptance angle, for which ϕ will become minimum, that is ϕ_c as shown in fig. 2.

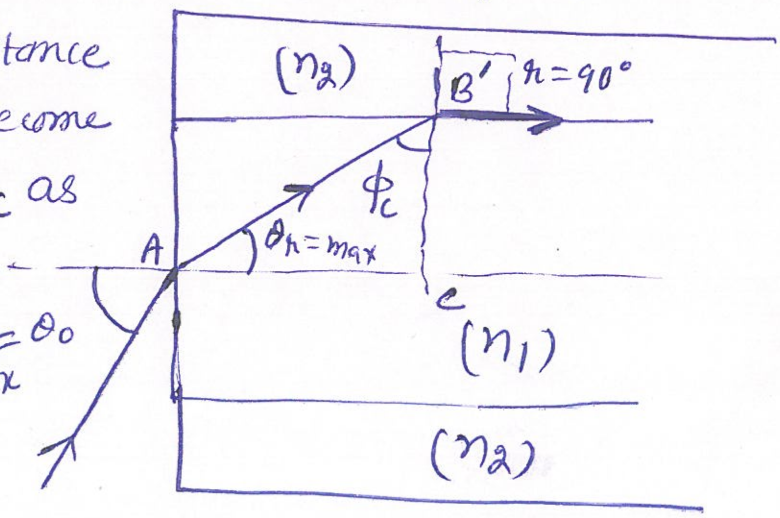


Fig 2.

Putting this condition $(\theta_i)_{max} = \theta_0$ in equation ②, we get

$$\sin\theta_0 = \frac{n_1}{n_0}\cos\phi_c$$
$$= \frac{n_1}{n_0}\sqrt{1-\sin^2\phi_c} \quad \text{—— (3)}$$

However, by applying Snell's law at point B', we can get

$$\sin\phi_c = \frac{n_2}{n_1} \quad \text{---} (4)$$

Put this value in (3), therefore

$$\sin\theta_0 = \frac{n_1}{n_0}\sqrt{1-\left(\frac{n_2}{n_1}\right)^2}$$

$$= \frac{n_1}{n_0} \times \frac{1}{n_1} \times \sqrt{n_1^2 - n_2^2}$$

$$\therefore \sin\theta_0 = \frac{1}{n_0}\sqrt{n_1^2 - n_2^2}$$

$$\text{or} \quad \boxed{\theta_0 = \sin^{-1}\left(\frac{1}{n_0}\sqrt{n_1^2 - n_2^2}\right)} \quad \text{---} (5)$$

Equation (5) gives expression for acceptence angle. Clearly its value depends on n_0, n_1 & n_2. For practical purposes the outside medium is usually air, therefore $n_0 = 1$ unless otherwise mentioned in the numericals.

Case I Numerical aperture (NA) :- It is defined as "Sine of acceptence angle."

$$\therefore \boxed{NA = \sin\theta_0} \quad \text{---} (6)$$

From (6) we see that it has no unit (i.e. it is just a number) and its value lies between 0 to 1.

The physical significance of NA can be stated as follows:- "NA of an optical fiber represents its light gathering ability."

If we insert value of θ_0 from (5) & (6), we get

$$NA = \sin\left[\sin^{-1}\left(\frac{1}{n_0}\sqrt{n_1^2 - n_2^2}\right)\right]$$

$$\Rightarrow \boxed{NA = \frac{1}{n_0}\sqrt{n_1^2 - n_2^2}} \quad \text{— (7)}$$

Equation (7) gives alternative expression for NA. We can write another expression for NA as follows:-

From (7) $NA = \frac{1}{n_0}\sqrt{n_1^2 - n_2^2}$

$$= \frac{1}{n_0}\sqrt{(n_1 - n_2)(n_1 + n_2)}$$

$$= \frac{1}{n_0}\sqrt{\left(\frac{n_1 - n_2}{n_1}\right)(n_1)(n_1 + n_2)} \quad \text{— (8)}$$

The quantity $\frac{n_1 - n_2}{n_1} = \Delta$ — (9)

is called fractional change in refractive index. Moreover, we can approximate $n_1 + n_2 \simeq n_1 + n_1 = 2n_1$, because the value of n_1 is very slightly greater than n_2 to minimize signal loss due to process of transition time dispersion delay or intermodal dispersion. Thus equation (8) can be approximated as:-

$$NA \simeq \frac{1}{n_0}\sqrt{\Delta (n_1)(2n_1)}$$

or $$\boxed{NA \simeq \frac{n_1}{n_0}\sqrt{2\Delta}} \quad \text{— (10)}$$

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Case II Acceptance cone :- "It is a cone of light rays formed

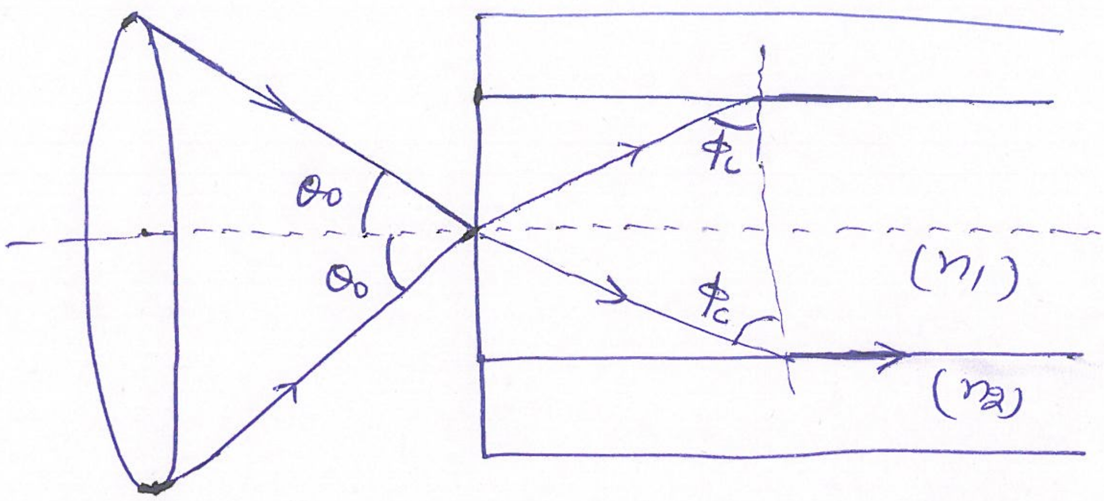

Fig 3.

at the input of optical fiber, which is coaxial with ~~the~~ fiber and whose semi vertical angle is equal to acceptance angle" as shown in fig 3. All light rays which enter in the fiber through acceptance cone will suffer TIRs at core-clad interface within optical fiber and ray of light incident on the fiber from outside ~~core-clad interface~~ of acceptance cone will not be able to suffer TIRs at core-clad interface and will be lost during transmission within the fiber.

"Only those sources of light are suitable for use with optical fiber, which can converge light rays within the acceptance cone of the fiber." This gives physical significance of acceptance cone. Such sources of light are only LEDs or semiconductor diode lasers.

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Mode of Light :- Mode of light can be defined either by using wave or ray nature of light. However for simplicity, we shall consider only ray nature of light here.

"A mode of light can be defined as distinct path followed by rays of light in travelling from one end to the other end of fiber."

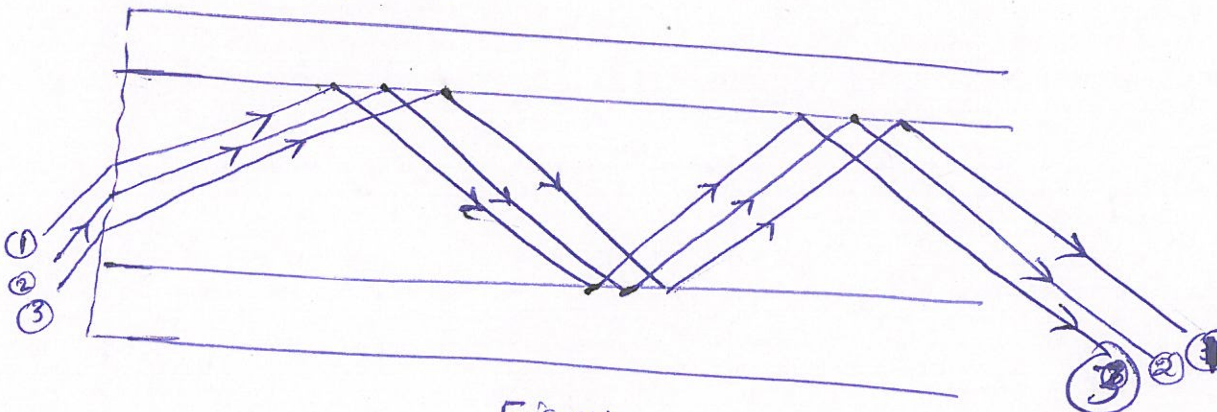

Fig (1)

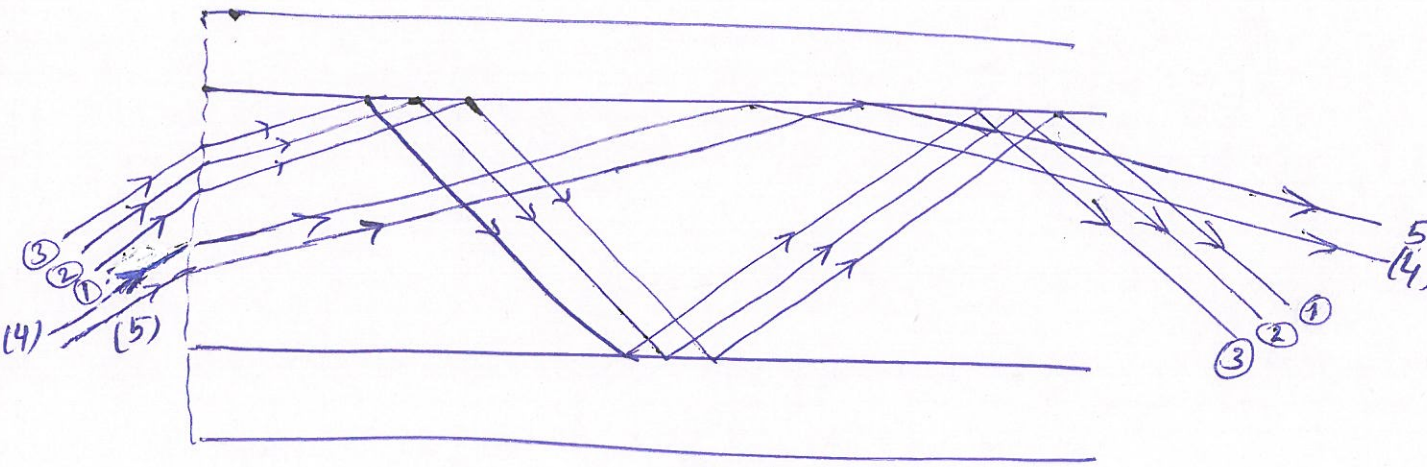

Fig (2)

In Fig. 1. shown here, three rays of light are entering in optical fiber such that all are parallel to each other. All these three rays travel along ~~parallel~~ identical paths, suffer equal number of reflections and take exactly same time to cover the length of fiber. Thus all these three rays belong to a single mode.

On the other hand in fig-(2), there are five rays shown. Three rays have one identical path and ray number (4),(5) have another identical path. Thus total number of modes in fig. (2) are two although number of rays are five.

~~Thats~~ Single Mode Fiber (SMF) and Multimode Fiber (MMF):-

A fiber is said to be SMF if only one mode of light can pass through it, while a fiber is said to be MMF, if more than one modes of light can travel through it.

In the previous article, fiber shown in fig. 1 is a SMF, because all three rays of light are entering in fiber at same angle with respect to axis. In general number of rays in SMF can be infinitely large, but all of these will enter in fiber as a beam of parallel rays.

In fig. 2. of previous article, two modes of light are propagating because there are two distinct angles, at which rays of light are entering in the fiber. Thus fiber shown in this figure is MMF. Note that in MMF, the total number of modes can be very large instead of just two as shown in fig. 2.

It is clear that total number of modes is equal to total number of distinct angles made by rays of light with axis at the input of fiber. It is also clear from fig. 1 & fig 2. of previous article that chances of interference between light rays (waves actually) during propagation are very ~~lag~~ large in MMF. During interference, the information being carried out by these light waves may be lost or may get distorted. Larger is the distance travelled in fiber, more will be chances of loss of ~~inf~~ information due to interference.

Thus for long distance communication, we must prefer SMF. On the other hand MMFs are used only for short distance communication.

In order to ensure that only a single mode of fiber should travel through optical fiber, the diameter of core must be kept very small, which is comparable with the wavelength of carrier waves.

Step index (SI) and Graded index (GRIN) fiber:- A fiber is said to be step index fiber (SI), if the refractive index of core (n_1) as well as clad (n_2) are constant.

Figure 1. shown below gives variation of refractive index of fiber as a function of distance (r) from the axis of fiber. Such a graph is called index profile of fiber.

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Since both n_1 & n_2 are constants, therefore, graph between refractive index and distance (r) from axis of fiber is horizontal straight line with the core (Region A to B) as well as within clad (Region AA' or BB').

But due to the fact that ($n_1 > n_2$, slightly), the shape of index profile appear to be similar to step of a ladder. Thus

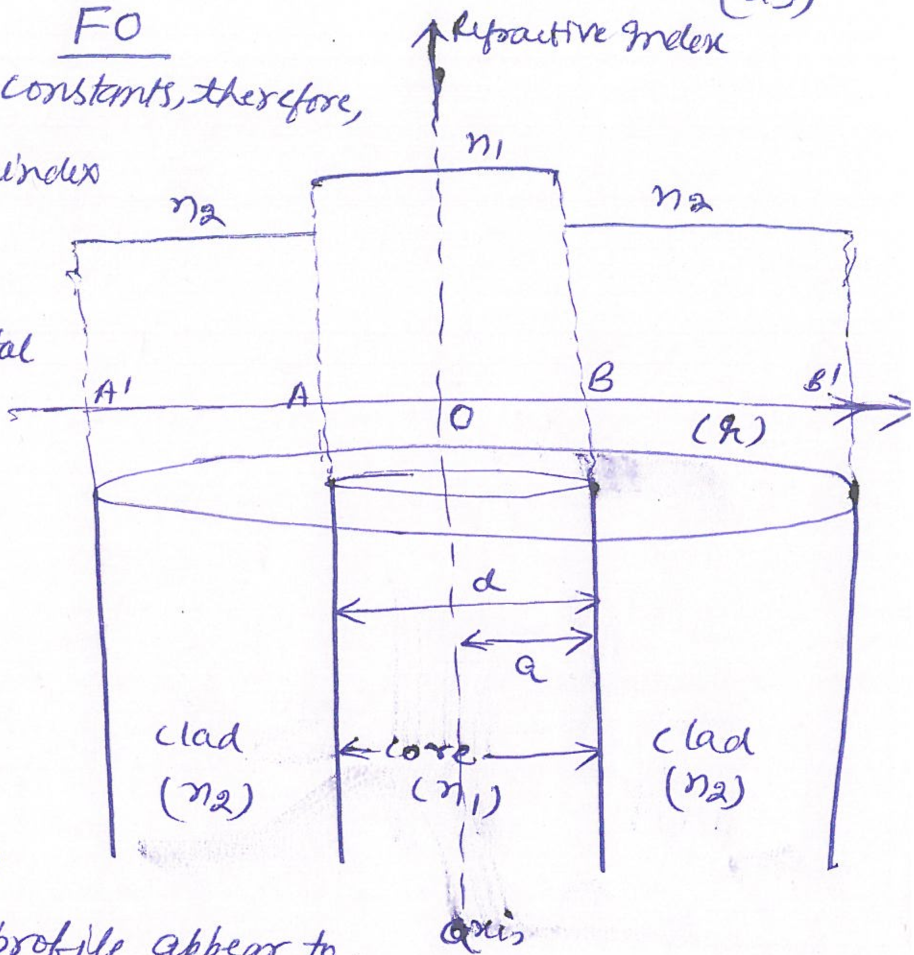


Fig 1.

Step index means sudden change in refractive index of fiber material at core-clad interface.

The working of SI fiber or propagation of light through a SI fiber is shown in fig.(2) at page no.(13) of these notes. From discuss given here, we can summarize following important points related with propagation of light through a SI fiber:

1. Each distinct ray (or mode) of light suffers exactly two refractions (one at input & other at output) for reaching from one end to other end of fiber.

2. Letters A, B, C ~~shoe~~ shown on each rays are actually different information packets which are being carried out ~~by~~ through optical fibers after converting into optical signal signals using appropriate devices (for example for speech transmission, microphone followed by LED can convert sound information into light signals). These signal packets (also called pulses) are usually of different frequencies (for example when we speak A, B or C, then frequency of sound waves is different for ~~all~~ these three alphabets, as a result, frequency of light waves produced using microphone+ LED combination will also be different). However carrier waves over which these different signal waves are superimposed are always of a ~~sign~~ single frequency and speed at which light will travel through fiber depends on the speed of carrier waves and ~~and~~ not on signal waves. Since all waves have carrier of same frequency, so they travel within fiber with same speed.

3. ~~Fibers~~ Light rays entering in fiber at different angles travel along different paths and suffer different number of reflections while travelling from one end to the other end.

~~4. Between two consecutive~~

4. Each ray suffers TIR at a point, which is always

located exactly at core-clad interface.

5. Between two successive TIRs, the path of light ray is a straight line.

6. Since speed of all light rays is same (because of single frequency of carrier) and path length of rays is different for different angles/paths, therefore different rays of light take different time ($\because$ time = $\frac{\text{distance}}{\text{speed}}$ or time $\propto$ distance as speed = constant) to come out of fiber, although all these rays have entered in fiber at the same time. Since rays are carrying identical information (for all rays in figure given on page 13, we have information of letter A, followed by B and then C), therefore at the out put all information packets belonging to a unique information will not be received at single instant of time, rather it will spread on small time interval (denoted by τ_{int} or Δt_{int}), which is called intermodal dispersion delay or transition time dispersion delay (for example according to fig 2 on page 13 of notes, first ray to reach out put will be (0), followed by rays (1) & (2) and information packet of A will be received when ray (0) reaches at output at time $t_0 = 0$, and information of A again reach at time t_1 when ray 2 reaches output, followed by another -

information packet at time t_2 when ray 3 reaches at output. If we assume that there are only three light rays, then for letter A, the intermodal dispersion delay is $\tau_{int} = t_2 - t_1$). Thus intermodal dispersion delay is present in SI fiber and it is an unwanted process, which leads to distortion/ loss of information within the fiber. For high quality transmission we must have $t_0 = t_1 = t_2$ etc. so that $\tau_{int} = 0$. This is possible if we keep ~~refractive~~ difference in refractive index of core and clad as small as possible i.e. $n_1 - n_2 \to 0$.

Thus due to this reason refractive index of clad is kept very close to refractive index of clad. If we use air as clad instead of glass then difference $n_1 - n_2$ will be very large ($\because n_1 \simeq$ glass $\simeq 1.5$ and $n_2 =$ air ≈ 1 $\Rightarrow n_1 - n_2 = 1.5 - 1 \simeq 0.5$ is very large on the other hand if $n_1 \simeq$ glass $\simeq 1.5$ and $n_2 \approx$ glass ≈ 1.49, then $n_1 - n_2 = 1.5 - 1.49 = 0.01$ is very small). Hence transition time dispersion will be very large if we take air as clad. This is not advisable and we must use a material of refractive index n_2, which is close to n_1 as clad so that transition time dispersion is minimum. Hence clad helps to minimize transition time dispersion.

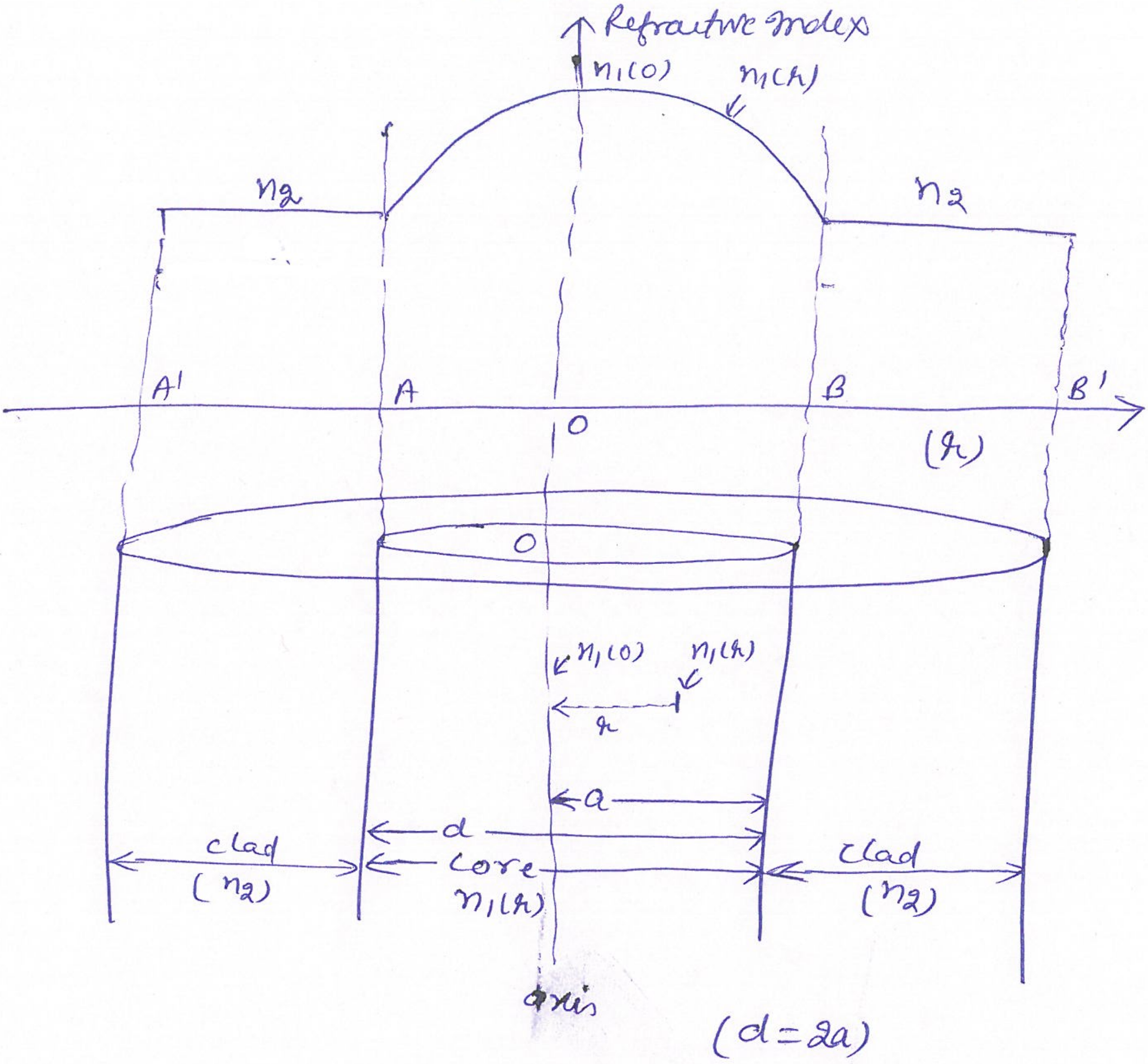


Fig (2)

GRIN Fiber: A fiber is said to be graded index fiber, if refractive index of core is maximum at its axis (at center) and decreases gradually toward clad, while refractive index of clad remains constant. The index profile of GRIN fiber is shown in fig (2). In 2-D the shape of profile within core is a curve and within clad, profile is horizontal straight line. The refractive index of fiber core is varied according to following expression:

$$n_1(r) = n_1(0)\sqrt{1-2\Delta\left(\frac{r}{a}\right)^{\alpha}} \quad \text{—①}$$

where a = core radius

r = distance of a point within core from its axis

$(0 \le r \le a)$

$n_1(0)$ = refractive index at axis/center of core

$n_1(r)$ = " " at distance r from center/axis of core

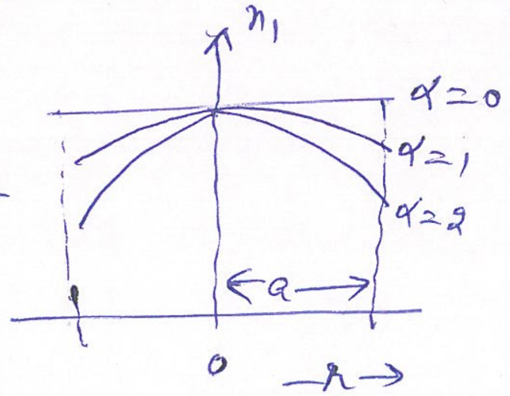
$$\Delta = \frac{n_1(0) - n_2}{n_1(0)} = \text{fractional change in refractive index}$$

α = index parameter

= it is a dimension less parameter, which is decided by fiber manufacturer

If $\alpha = 0$, then $\left(\frac{r}{a}\right)^{\alpha} = \left(\frac{r}{a}\right)^{0} = 1$

$\therefore n_1(r) = n_1(0)\sqrt{1-2\Delta}$ = constant



$\therefore$ Fiber becomes step index fiber.

Fig. 3.

Larger value of α means faster change in refractive index of core as shown in fig. (3).

Default value of α is taken as 2, for which the shape of index profile within core is a parabola. Normally it is not possible to change refractive index of core continuously, rather we chose different layers in fiber core as shown in fig 4.

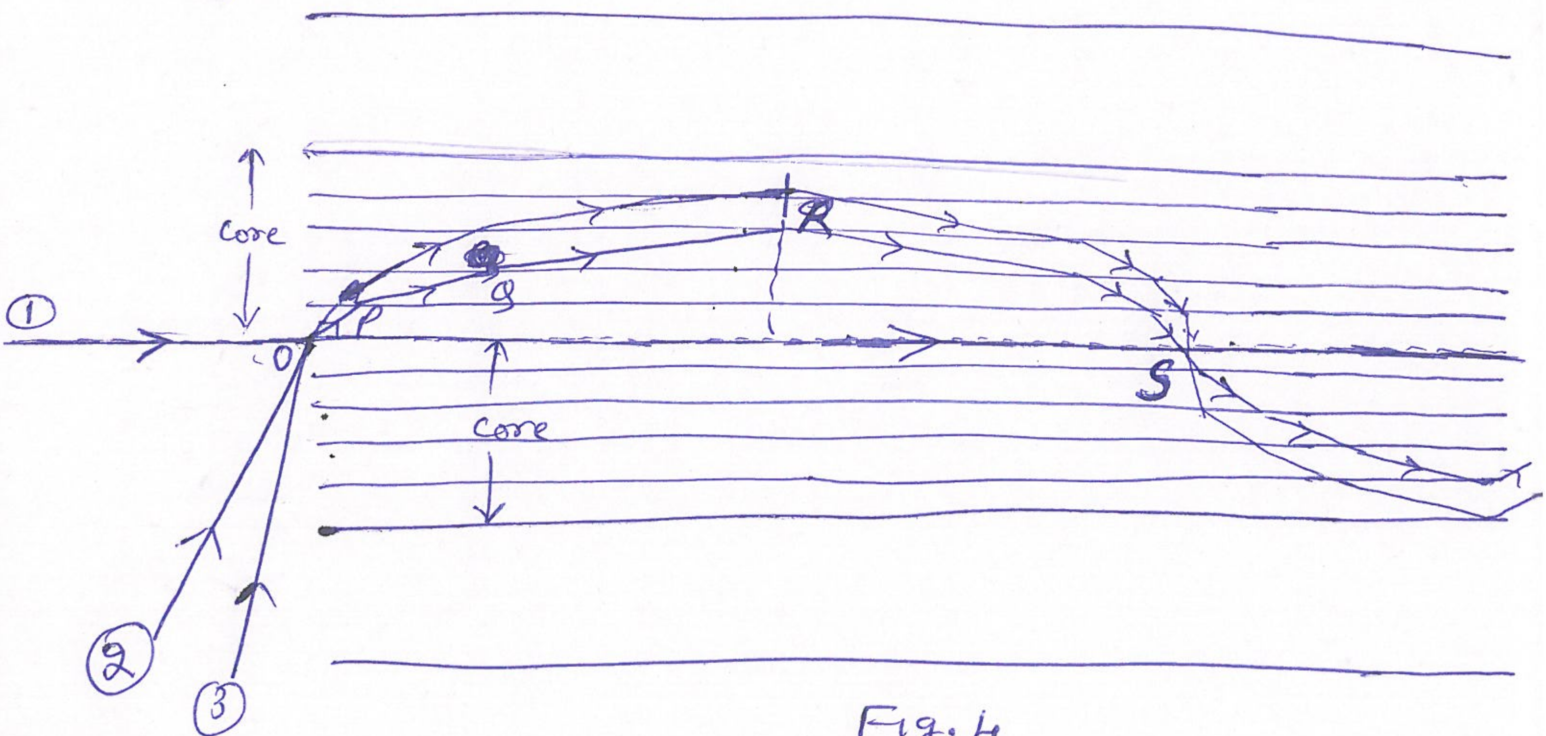


Fig. 4

Here refractive index of fiber in each layer is kept constant, but refractive index of each outer layer of core is slightly less than that of inner layer.

Now consider ray ①, which is traveling along axis of fiber. This ray covers shortest path in the fiber, however due to maximum refractive index of innermost layer, speed of this ray is minimum.

Now consider ray no. ②, which is incident obliquely in the fiber. On entering in innermost core layer, it bends toward axis and follows path OP, at P it enters in second layer of core, whose refractive index is slightly less than that of innermost layer, so it bends away from normal and follows path PQ. At Q it enters layer 3 of core which is of still smaller refractive index and follows path QR by bending away from normal. Thus with consecutive refractions the angle of incidence at interface between two core layers goes on increasing and as soon as it becomes more than critical angle (say at point R), the ray ~~bends~~ suffers TIR and start reaching toward axis of fiber. Now it is travelling from rarer to denser medium and therefore it bends toward normal.

Although ray 2 has traveled longer distance, but the medium in which, it has traveled (outer layers of core) has less refractive index than ~~that~~ that ray 1. So average speed of ray 2 is more than that of ray 1. Thus ~~to~~ both rays reach point S of axis at same time although one has covered smaller distance and other has covered larger distance.

Therefore in graded index fiber, it is possible to make time taken to cover the fiber length independent of angle of incidence, so that transition time dispersion delay is minimum/eliminated.

The propagation of light waves through ideal graded index fiber (in which refractive index of core charges gradually ~~and~~ but continuously) is shown in fig. 5.

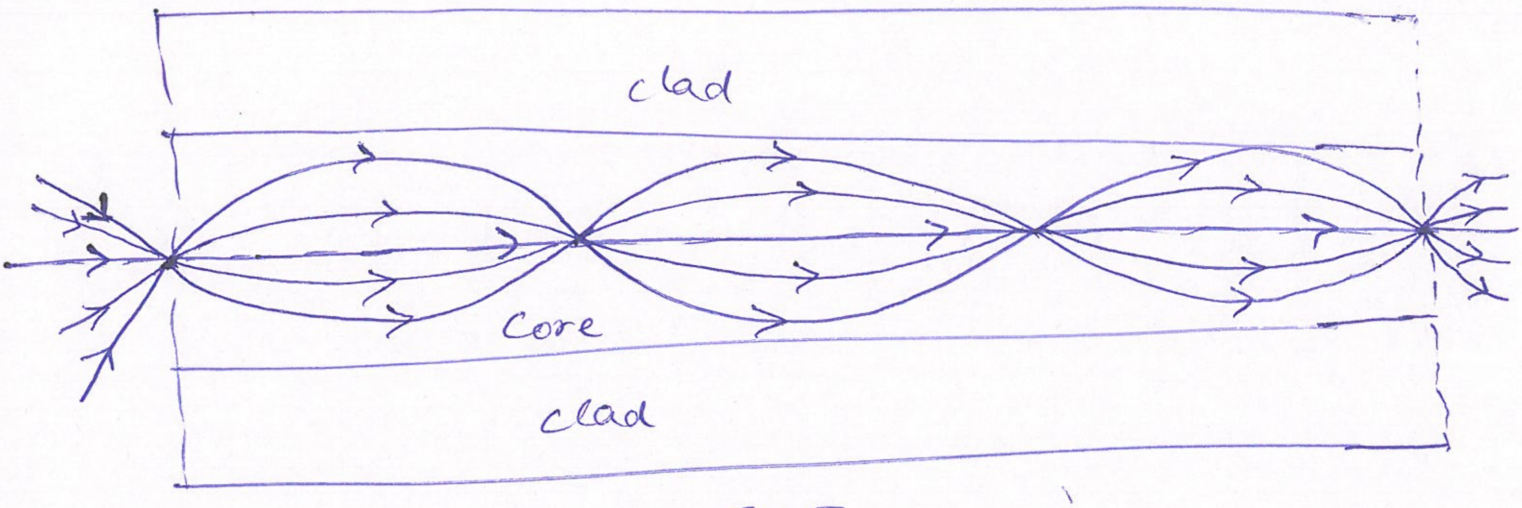


Fig. 5.

From above discussion, we can summarize the working of graded index fiber as follows:-

1. Light propagation within fiber is due to refractions as well as TIRs.
2. Total number of refractions per ray are countless.
3. Rays travelling near axis have low speed and those traveling away from axis have high speed.
4. Rays entering fiber at different angles travel along different paths.
5. ~~TIR~~ TIR may take place even before core-clad interface.
6. Path of ray of light between two successive TIRs is not a straight line.
7. Since speed of light rays is proportional to the distance travelled, therefore time taken by rays of light to cross the fiber length is independent of path/angle. Hence transition time dispersion delay can be eleminated.